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LAMINAR FLOW INTEGRATION - FLIGHT TESTS
STATUS AND PLANS

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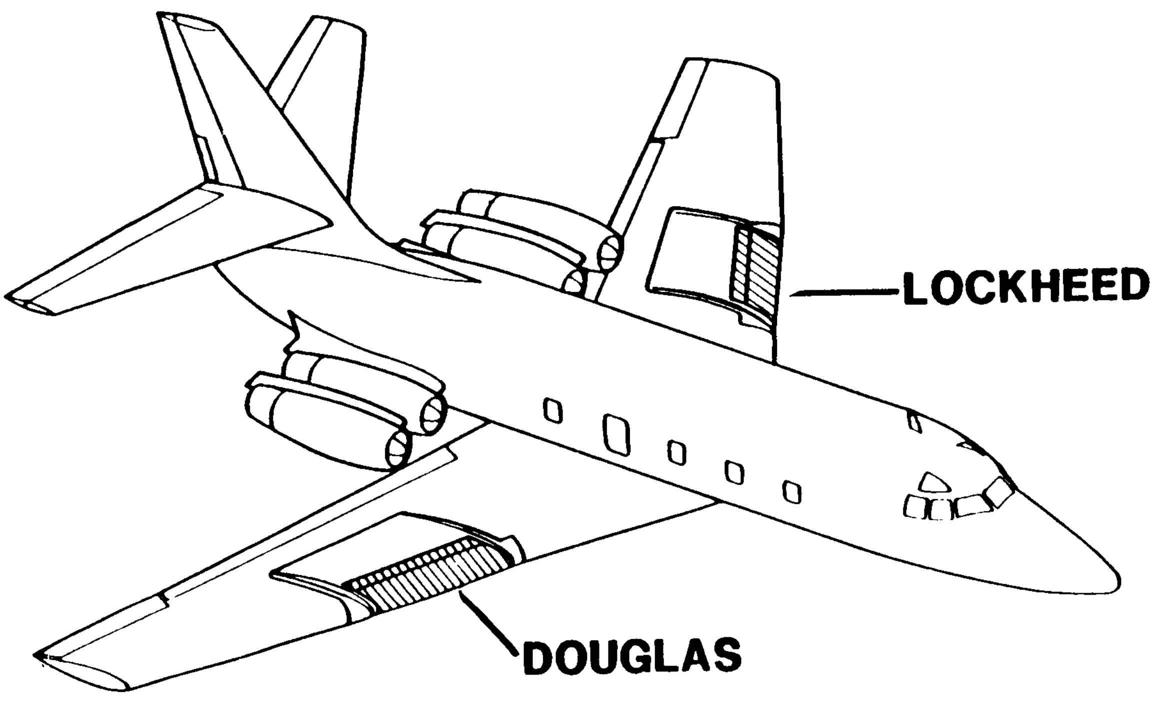
[redacted]INAR FLOW INTEGRATION - FLIGHT TESTS

Under the Aircraft Energy Efficiency - Laminar Flow Control Program in the Projects Directorate at the Langley Research Center, there are currently three flight tests programs under way to address critical issues concerning laminar flow technology application to commercial transports (ref. 1). The Leading-Edge Flight Test (LEFT) with a JetStar aircraft is a cooperative effort with the Ames/Dryden Flight Research Facility to provide operational experience with candidate leading-edge systems representative of those that might be used on a future transport. In the Variable Sweep Transition Flight Experiment (VSTFE), also a cooperative effort between Langley and Ames/Dryden, basic transition data on an F-14 wing with variable sweep will be obtained to provide a data base for laminar flow wing design. Finally, under contract to the Boeing Company, the acoustic environment on the wing of a 757 aircraft will be measured and the influence of engine noise on laminar flow determined with a natural laminar flow glove on the wing. This presentation reports the status and plans for these programs.

- **LEADING EDGE FLIGHT TEST - JETSTAR**
- **VARIABLE SWEEP TRANSITION FLIGHT EXPERIMENT - F-14**
- **WING NOISE SURVEY AND NLF GLOVE FLIGHT TEST - 757**

LAMINAR FLOW CONTROL LEADING-EDGE FLIGHT TEST

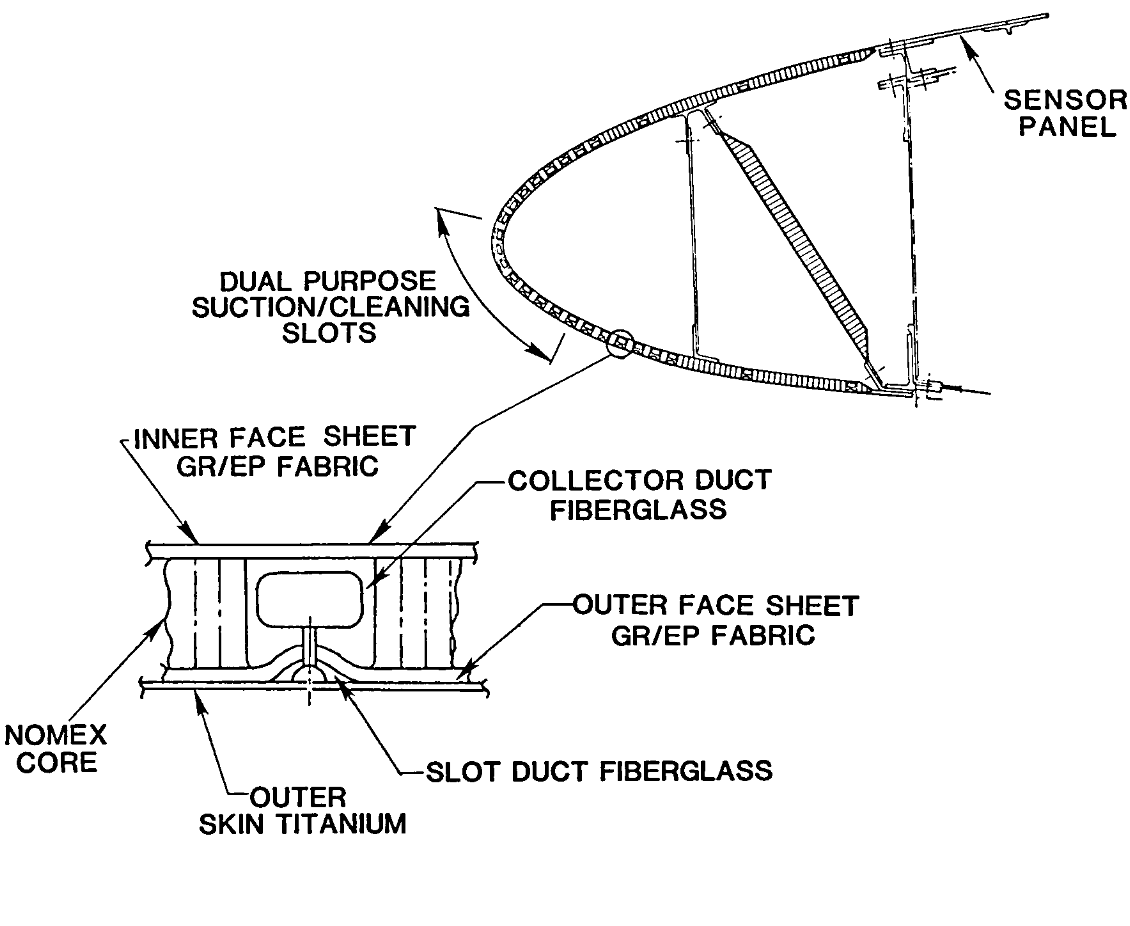
The most difficult problems of achieving laminar flow on commercial transports appear to be associated with the leading-edge region. Solutions to these problems will remove many concerns about the ultimate practicality of laminar flow. A flight program is currently under way within NASA to evaluate the effectiveness of integrated LFC leading-edge systems developed by Douglas and Lockheed over the past few years. Under NASA contracts, both companies have designed and fabricated a leading-edge test article to be installed on a JetStar to demonstrate that the required systems can be packaged into a leading-edge section representative of future LFC commercial transport aircraft, and that these systems can operate reliably with minimum maintenance in an airline flight environment.



OBJECTIVE: DEMONSTRATE THE EFFECTIVENESS AND PRACTICALITY OF L.E. SYSTEMS IN MAINTAINING LAMINAR FLOW UNDER REPRESENTATIVE FLIGHT CONDITIONS

LEADING-EDGE FLIGHT TEST
LOCKHEED TEST ARTICLE

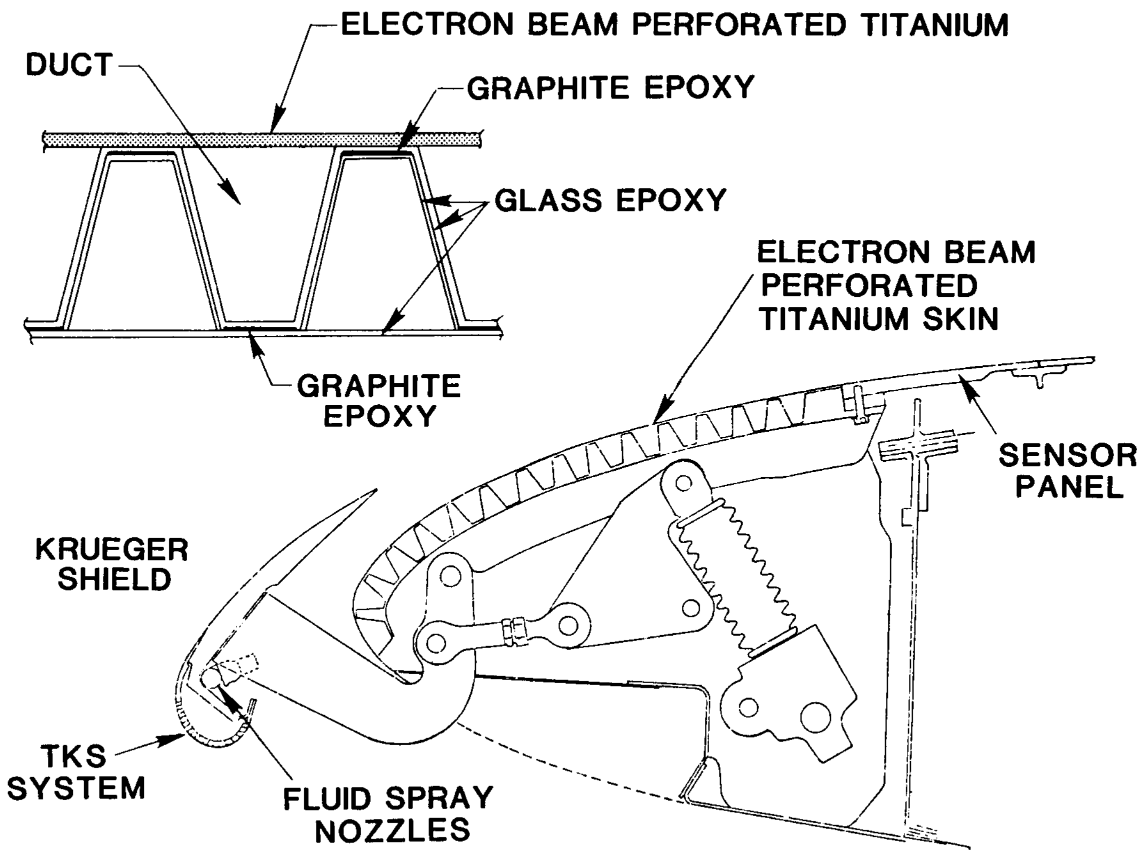
The Lockheed leading-edge concept (ref. 2) is illustrated in this figure. The leading-edge box structure is a sandwich construction. A 0.016-in. thick titanium outer sheet is bonded to a sandwich substructure of graphite/epoxy face sheets with a Nomex honeycomb core. Suction is accomplished through 27 fine, spanwise slots (0.004 inch in width) distributed chordwise on both the upper and lower surfaces back to the front spar. The suction flow is routed through the structure by a combination of slot ducts, metering holes and collector ducts embedded in the honeycomb. The Lockheed insect protection system is integrated with the anti-icing protection system. It consists of dispensing a cleaning/anti-icing fluid over the surface through slots above and below the attachment line (previous studies (ref. 2) have shown that insects will not adhere to a wet wing). These slots are purged of fluid during climb-out and provide suction to achieve laminar boundary layer flow at cruise conditions.



LEADING-EDGE FLIGHT TEST
DOUGLAS TEST ARTICLE

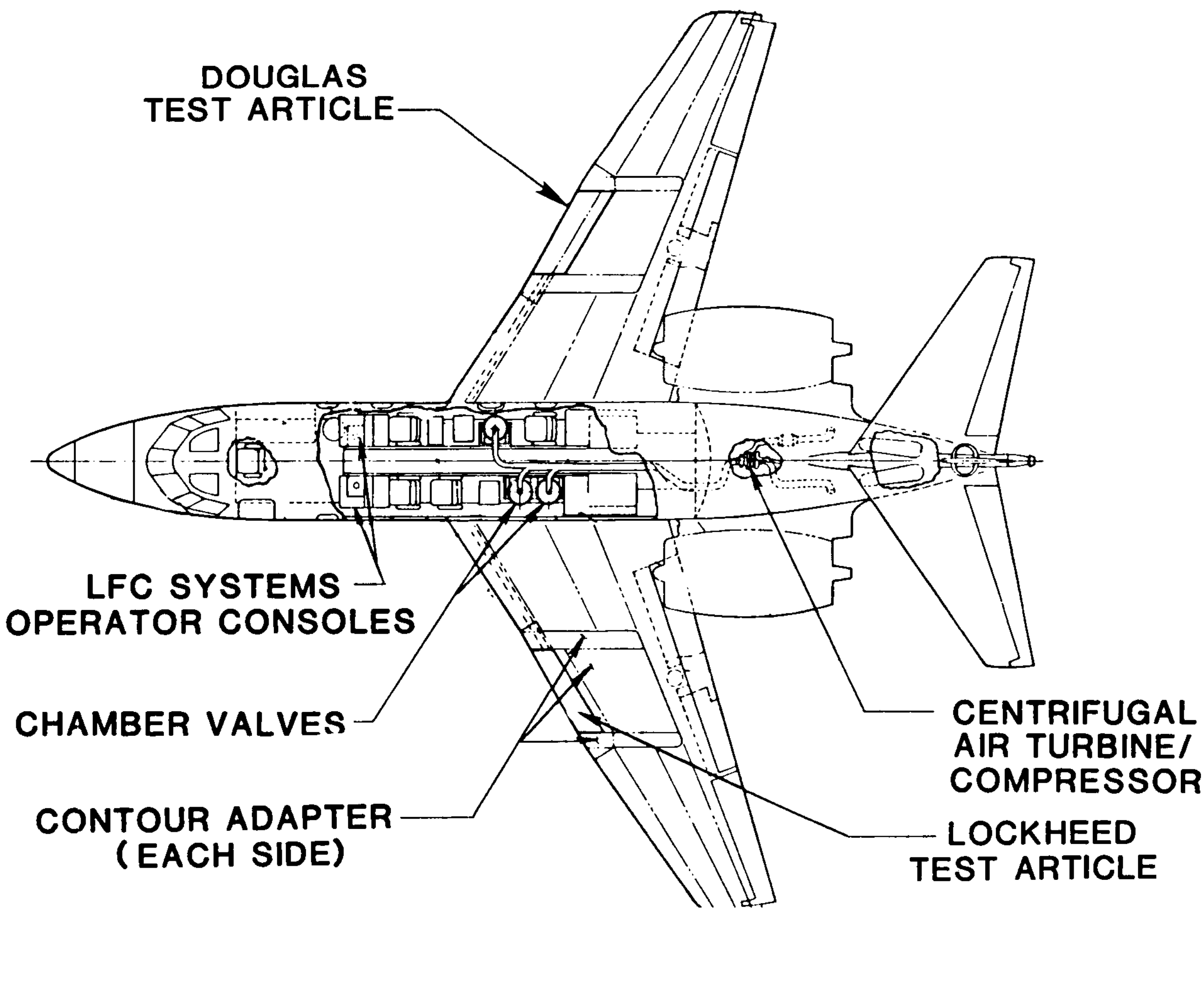
The Douglas leading-edge concept (ref. 3) illustrated in the figure consists of an electron-beam perforated (EBP) titanium sheet bonded to a fiberglass sandwich substructure which forms a suction panel. This removable suction panel is attached to a ribbed supporting substructure. The areas where the EBP skin bonds to the corrugated substructure are impervious to flow; thus, suction is through perforated strips. Alternate substructure flutes are used for suction air collection. Suction is applied only on the upper surface from just below the attachment line to the front spar. A Krueger-type flap serves as a protective shield against insect impact. Spray nozzles on the underside of the Krueger shield provide added insect protection and are a part of the leading-edge anti-icing protection. These nozzles coat the leading-edge with a freezing point depressant fluid to provide protection against lighter insects which might impinge on the wing. In icing conditions, the Krueger serves as the primary anti-icing protection of the leading edge, supplemented as required with the spray nozzle system. The shield leading edge is equipped with a TKS* (commercially available) ice protection system. A system for purging fluid from the suction flutes and surface perforations is provided if required.

*TKS Aircraft Deicing Ltd., England.



JETSTAR LEFT CONFIGURATION

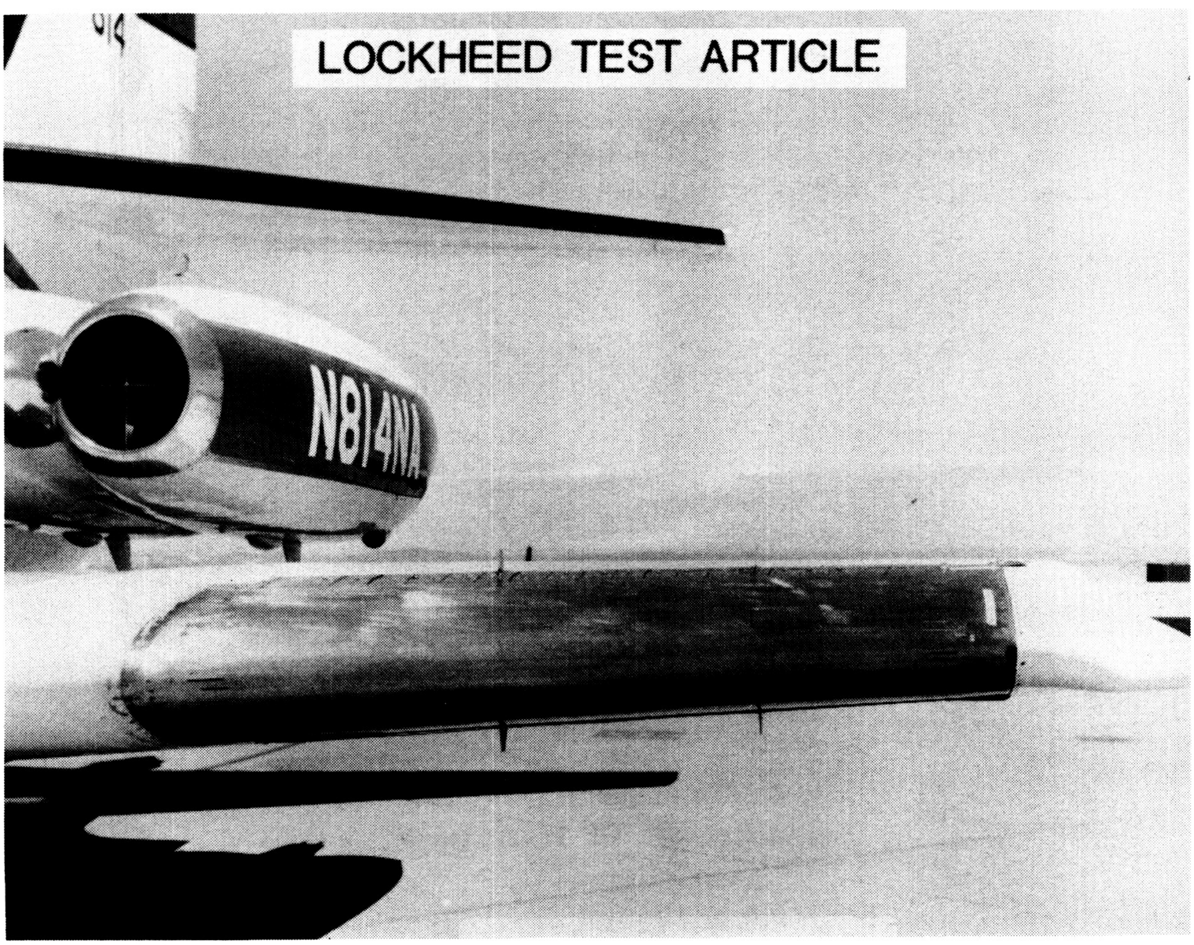
A schematic of the JetStar configured for the leading-edge flight test program is presented in this figure. The heart of the suction system is the centrifugal air turbine compressor used as a suction pump. The compressor is mounted in the unpressurized rear fuselage compartment of the JetStar. To enchance the research value of the flight test, to allow the control and measurement of key parameters, and to permit optimization of the systems, each of the 15 suction strips on the Douglas test article and each of the 27 slots on the Lockheed test article have individual flow adjustment control. Individual flow control is accomplished through the use of chamber valves. One chamber valve handles the 15 Douglas suction lines and there are two valves: one chamber valve for the Lockheed upper surface lines and one chamber valve for the Lockheed lower surface lines. Each suction line has its own needle valve within the chamber valve to adjust the suction flow. Control of the chamber valves and data acquisition is accomplished at two operator consoles and one data console in the cabin.



LOCKHEED TEST ARTICLE

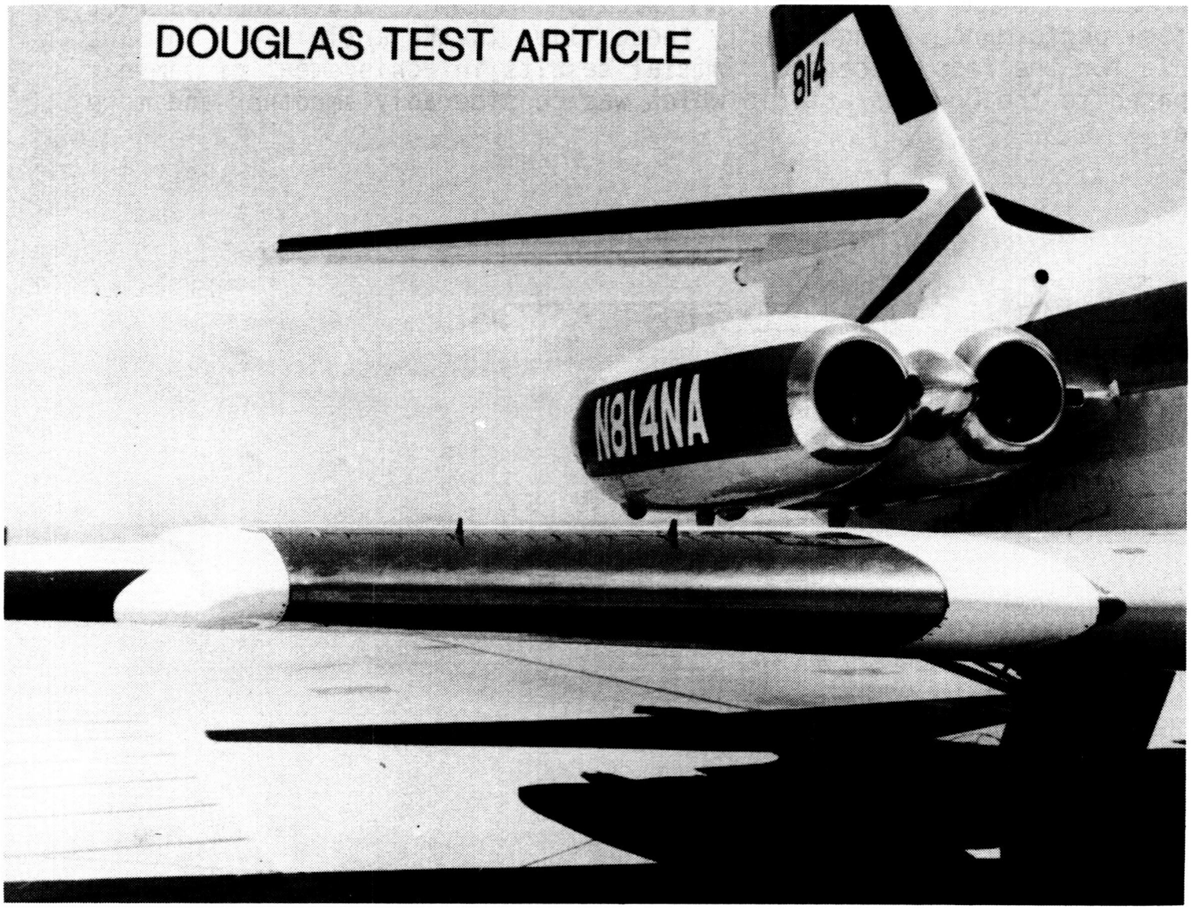
The photograph shows the Lockheed test article. Note the instrumentation at the front spar on the upper and lower surfaces. Two reference pitot tubes are shown mounted on struts about two inches above the wing surface. Twenty equally spaced spanwise pitot tubes at the front spar (about 0.060 inches above the wing surface) are used to determine whether the boundary layer is laminar or turbulent.

In the fabrication of the Lockheed test article, a number of difficult fabrication problems were encountered which led to a surface quality that was only marginally acceptable in terms of meeting laminar flow smoothness and waviness criteria. During fabrication, adhesive flow into subsurface plenums also resulted in repairs and residual suction blockage that could affect laminar flow performance. Undoubtedly these flaws in the article are in part responsible for the less successful initial results in achievement of laminar flow compared to the Douglas article which was considerably smoother and more wave-free.



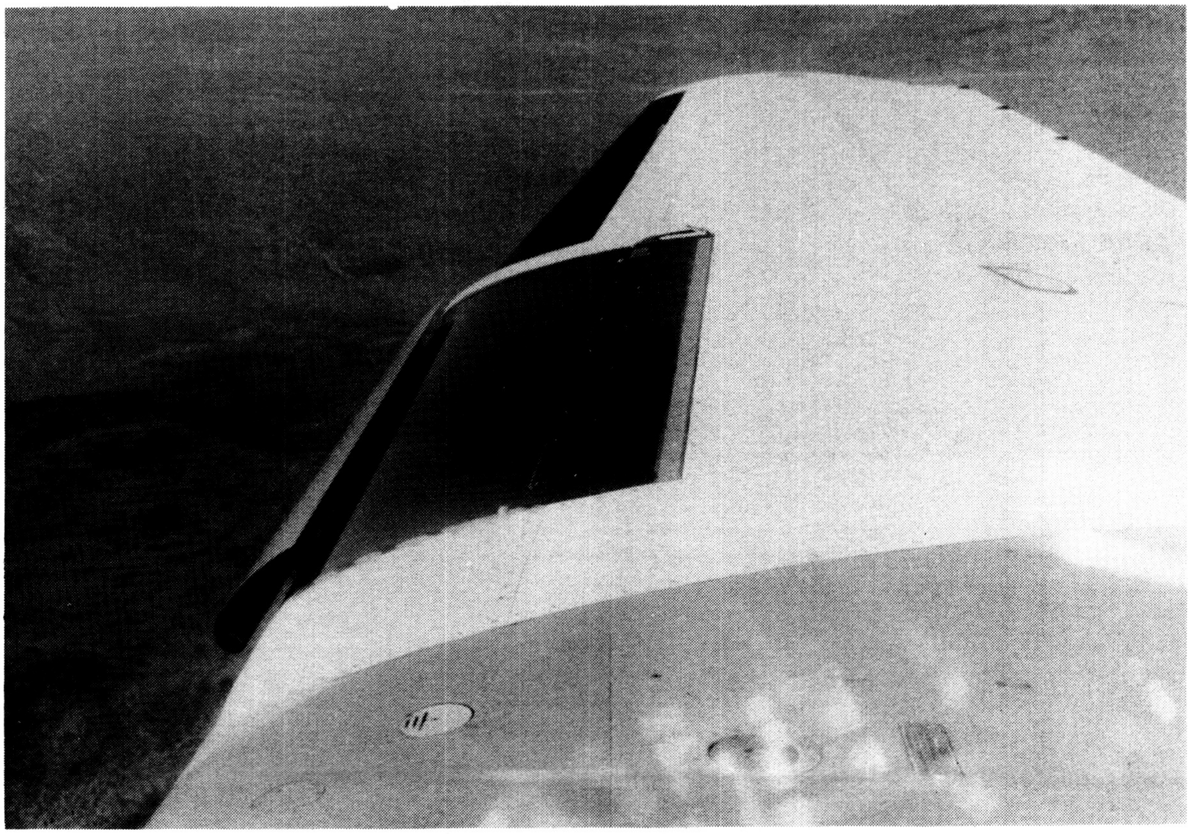
DOUGLAS TEST ARTICLE

The photograph shows the Douglas test article installed on the JetStar. The white areas inboard and outboard of the test article are aerodynamic fairings which fair the test article contour back to the JetStar wing surface. Aft of the front spar, a fairing also extends to the rear spar to close out the wing sections. The step in the outboard fairing is indicative of how much thicker the new wing sections are relative to the basic wing. Back to the front spar the LEFT section on the JetStar is roughly about the same size as the forward wing sections on a DC-9-30 at the mean aerodynamic chord.



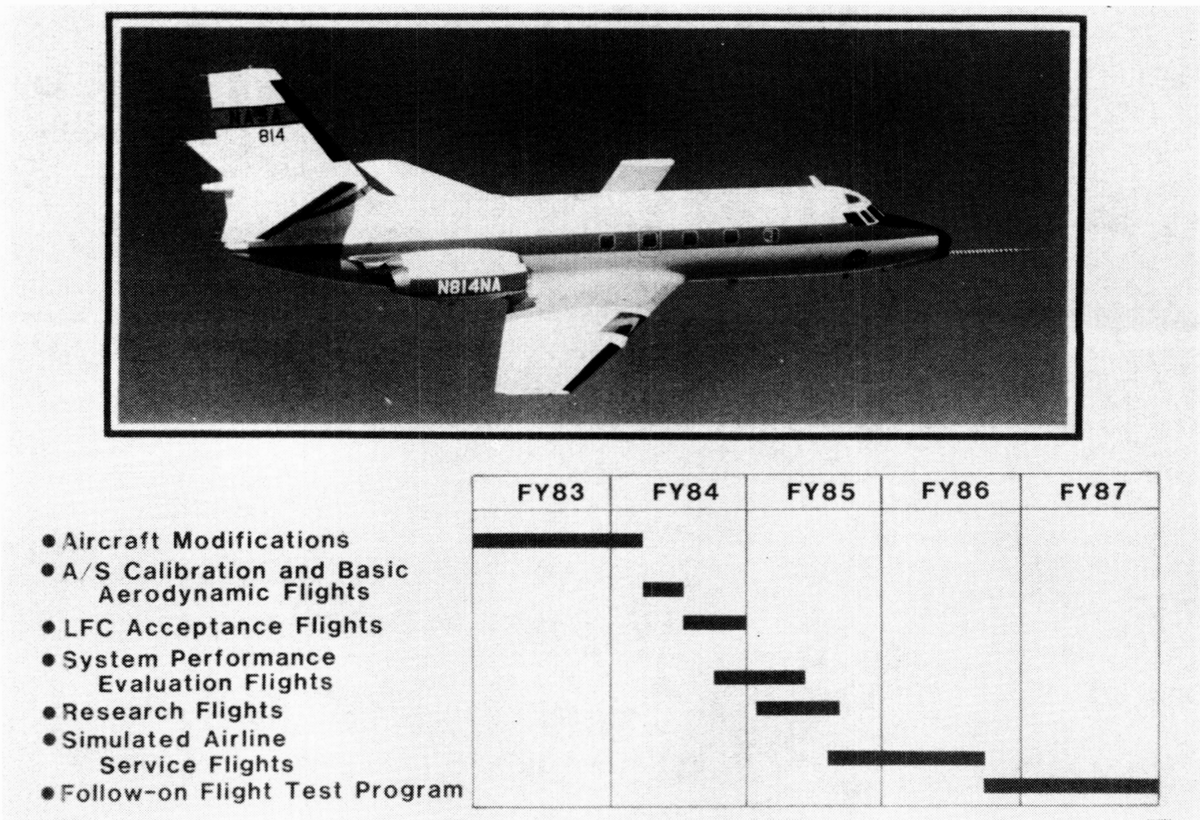
DEPLOYED DOUGLAS INSECT SHIELD

This photograph shows the Douglas insect shield deployed. The shield is deployed at takeoff and retracted at about 6000 feet altitude. During descent, the shield is deployed at 6000 feet. In the event of an ice encounter, the aircraft reduces speed to M=0.4 and the shield is then deployed. A freezing point depressant fluid spray system, located on the underside of the Krueger, is used if required for supplemental insect and ice protection.

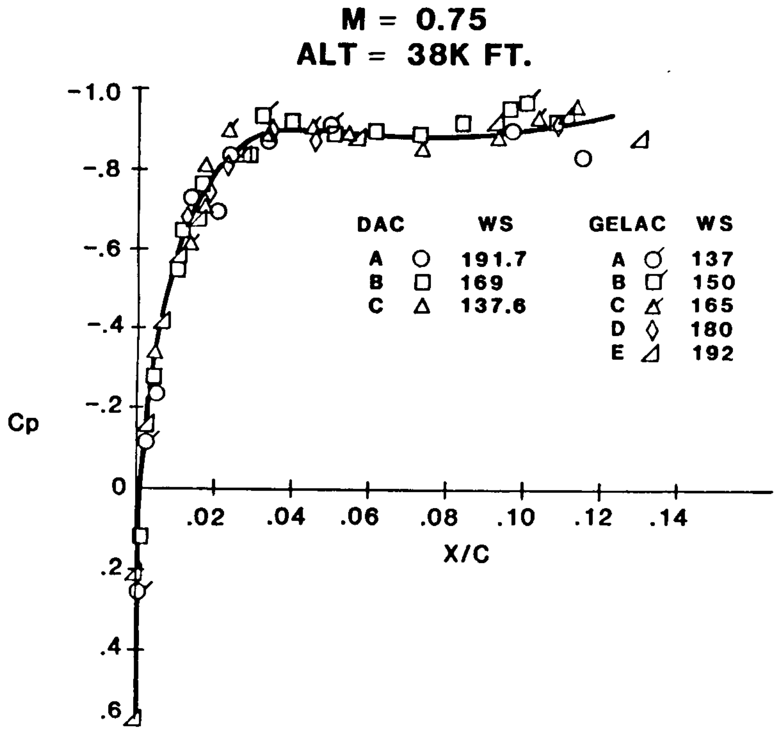


LEFT JETSTAR AND FLIGHT TEST SCHEDULE

The aircraft modifications were completed in FY '84 and the first flight of the aircraft took place in December 1983. Acceptance testing and performance evaluation of the new systems extended through FY '84. During the research flights, the laminar flow performance is to be optimized. Simulated service flights will begin in mid FY 85. These will be structured to gain operational experience with the test articles.

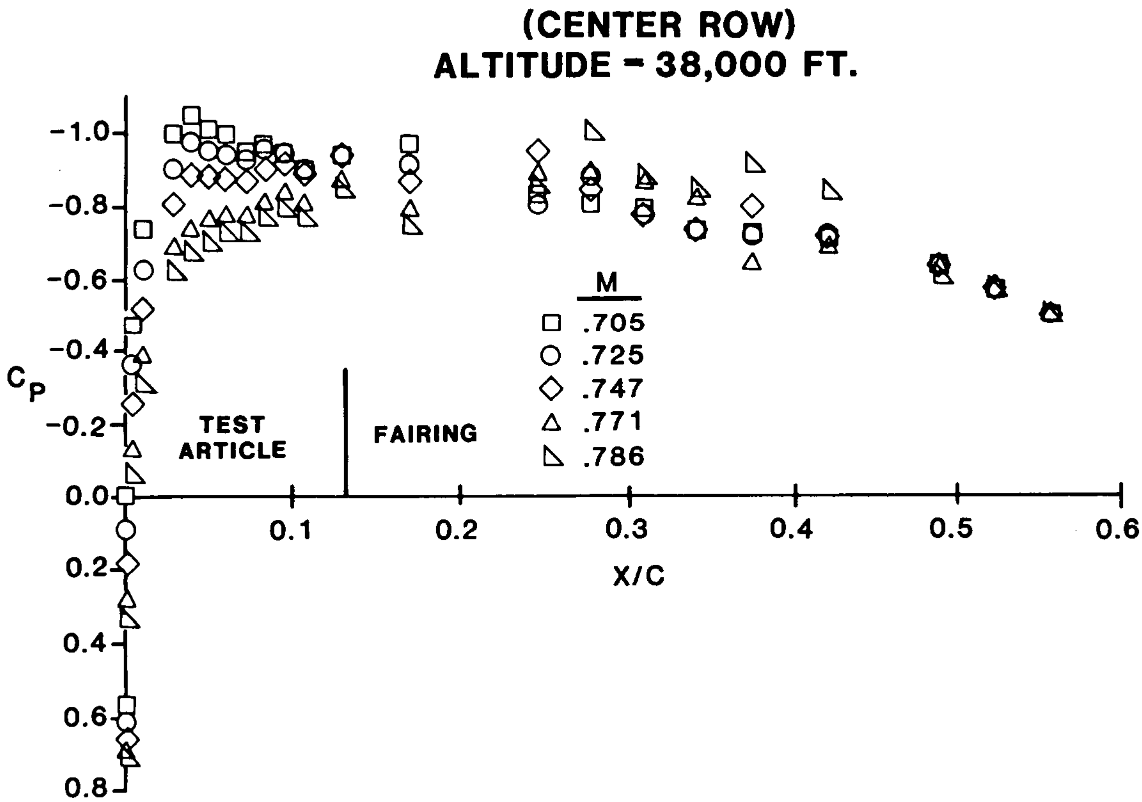


At the design point, M = 0.75 at 38,000 feet altitude, the chordwise pressure distribution at three span stations on the Douglas test article and five span stations on the Lockheed test article are shown. The solid line is a data fairing. The flight results are quite close to the desired pressure distribution and have acceptable spanwise gradients.



DOUGLAS TEST ARTICLE SURFACE PRESSURES

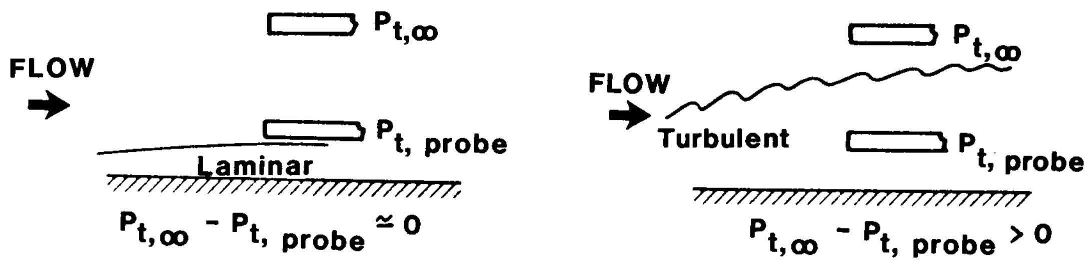
Extended pressure distributions back to the rear spar are shown. The data consist of only the Douglas test article mid span row of surface pressures at 38,000 feet altitude. The pressure distribution becomes "peaky" at the lower Mach number, and above the design point Mach number .75, a favorable gradient exists to the front spar.

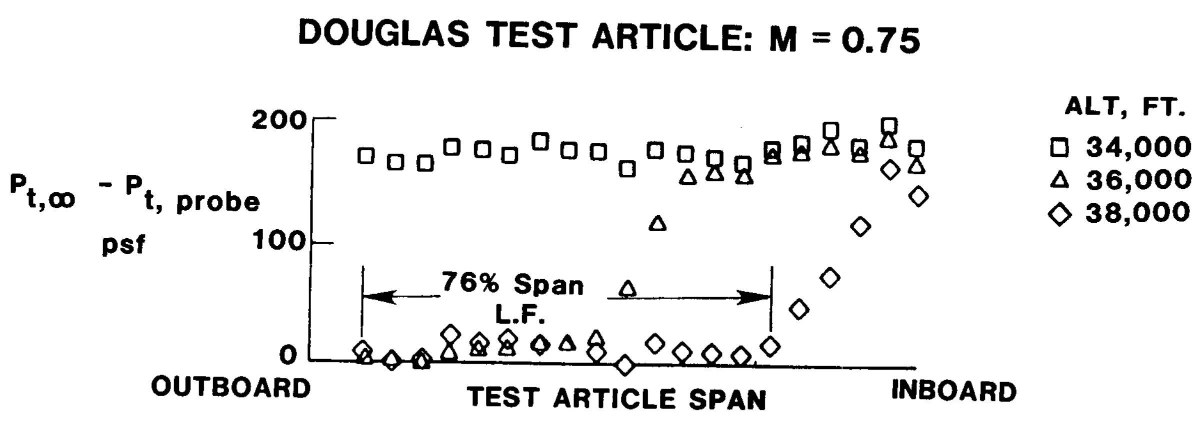


DETERMINATION OF SPANWISE EXTENT OF LAMINAR FLOW AT FRONT SPAR

This figure illustrates how pitot tubes near the surface (about 0.06 inch above the surface) are used to detect the nature of the boundary layer. If laminar flow exists at the pitot tube, the boundary layer will be thin enough to pass under the tube which will then register the same pressure as the reference probe, two inches above the surface. If transition occurs ahead of the near-to-surface pitot tube, it will be emersed in a turbulent boundary layer with much reduced pitot pressure, depending upon where transition occurs.

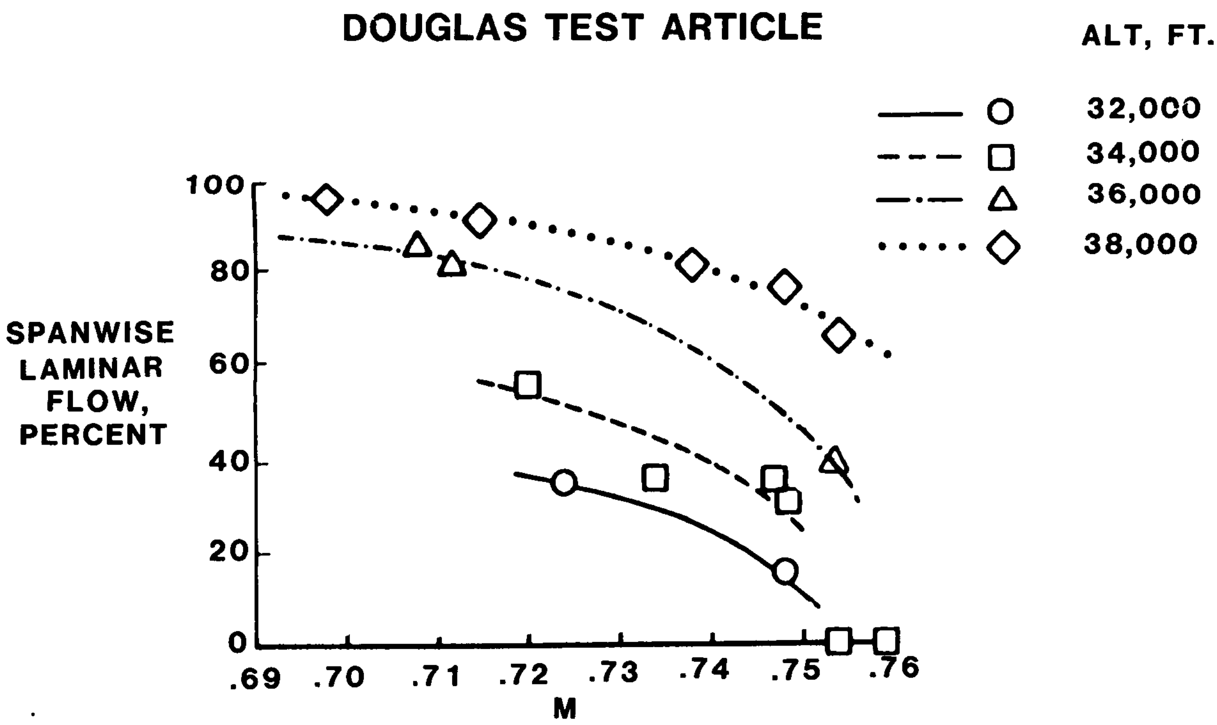
Data taken in the initial flights on the Douglas test article show the pressure differentials that exist on twenty pitot tubes spaced about two inches apart across the front spar. At the design point, M = .75 at 38,000 feet altitude, the outboard 76% of the test article span is laminar at the front spar. The inboard region is turbulent and the readings near 200 psf differential pressure indicate that transition occurs at or near the attachment line for those inboard span stations. At lower altitudes this turbulent region spreads outboard, until at 34,000 feet the entire span of pitot data indicates that transition occurs on the attachment line.





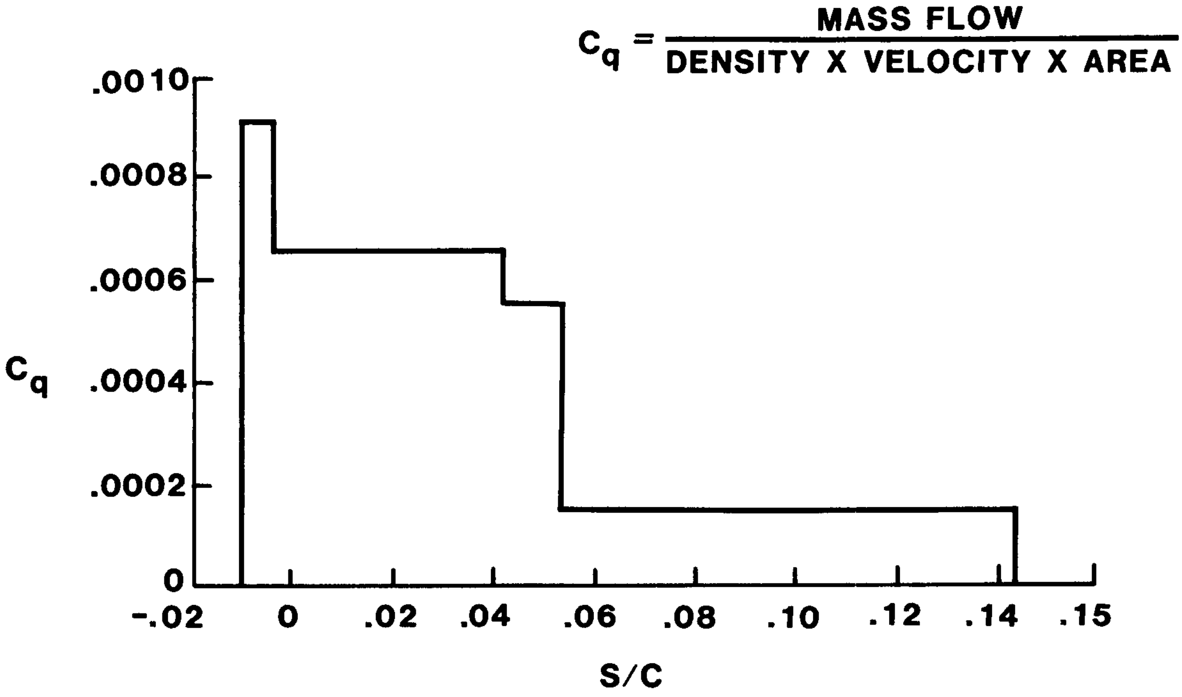
SPANWISE EXTENT OF LAMINAR FLOW AT FRONT SPAR (INITIAL FINDINGS)

These data were obtained from the initial flights to assess the laminar flow performance of the test articles. The spanwise extent of laminar flow, as determined from the twenty pitot tubes, is shown over the cruise altitude and Mach number range of the JetStar. The results were disappointing because turbulence contamination from the inboard region of the wing resulted in only a limited Mach number and altitude range for which full span laminar flow was observed. On the Lockheed test article, no laminar flow at the front spar was observed except when the aircraft was side-slipped to lower the effective sweep of the Lockheed test article leading edge. These data indicated the need to employ some method to suppress the leading-edge turbulence contamination.



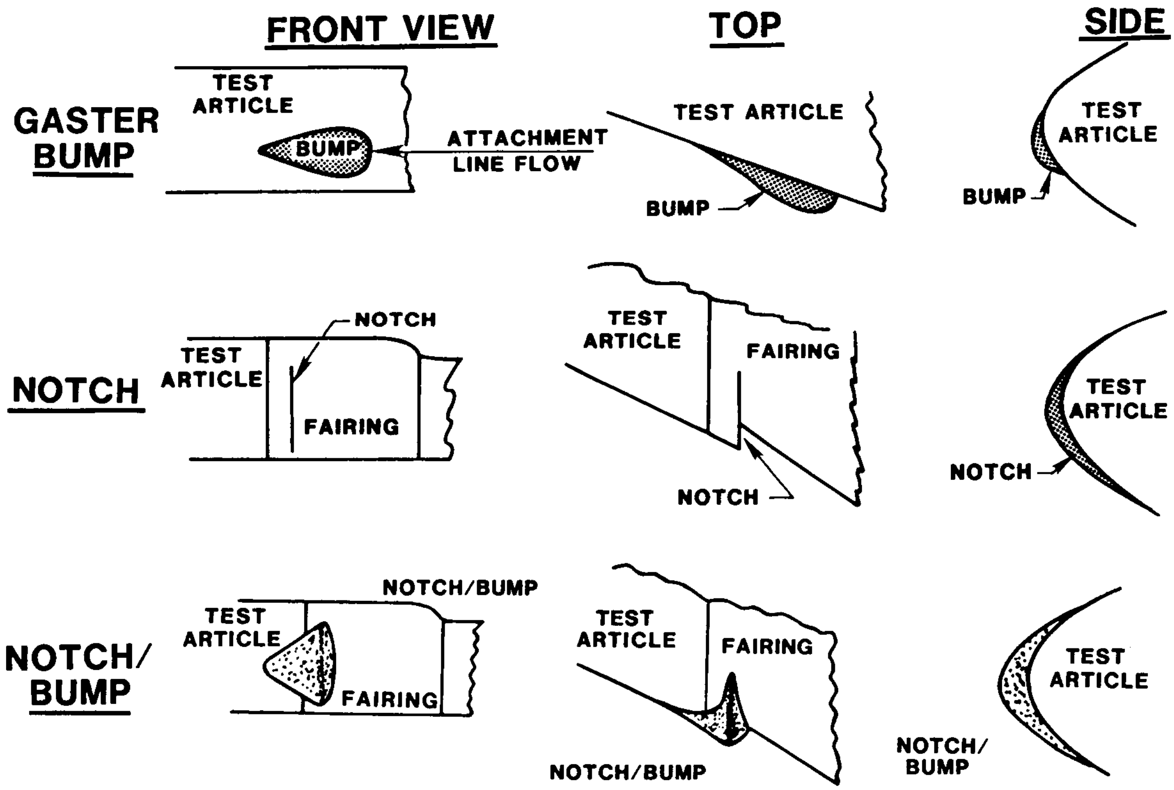
NOMINAL SUCTION DISTRIBUTION
DOUGLAS TEST ARTICLE

The design nominal suction distribution was used for all flights. The higher suction level in the forward region of the test article is required to control crossflow instabilities; the aft, lower level suction controls the growth of Tollmien-Schlichting disturbances.



CANDIDATE METHODS TO CONTROL ATTACHMENT LINE CONTAMINATION

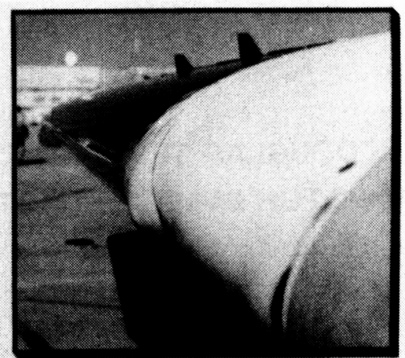
Three approaches to control spanwise turbulence contamination at the leading edge were examined. A Gaster bump (ref. 4) and a notch are simple devices placed on the wing inboard of the test article. The intent of these devices is to establish a new laminar attachment line from the stagnation point created by the bump or notch. The Gaster bump was found to be effective over a limited range of angle of attack, but the notch was ineffective. The best results were obtained with a combination notch/bump.



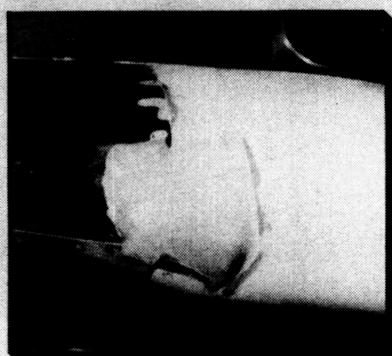
DOUGLAS NOTCH/BUMP

This figure is a three view of the final configuration of the combination notch/bump.

PLANFORM VIEW



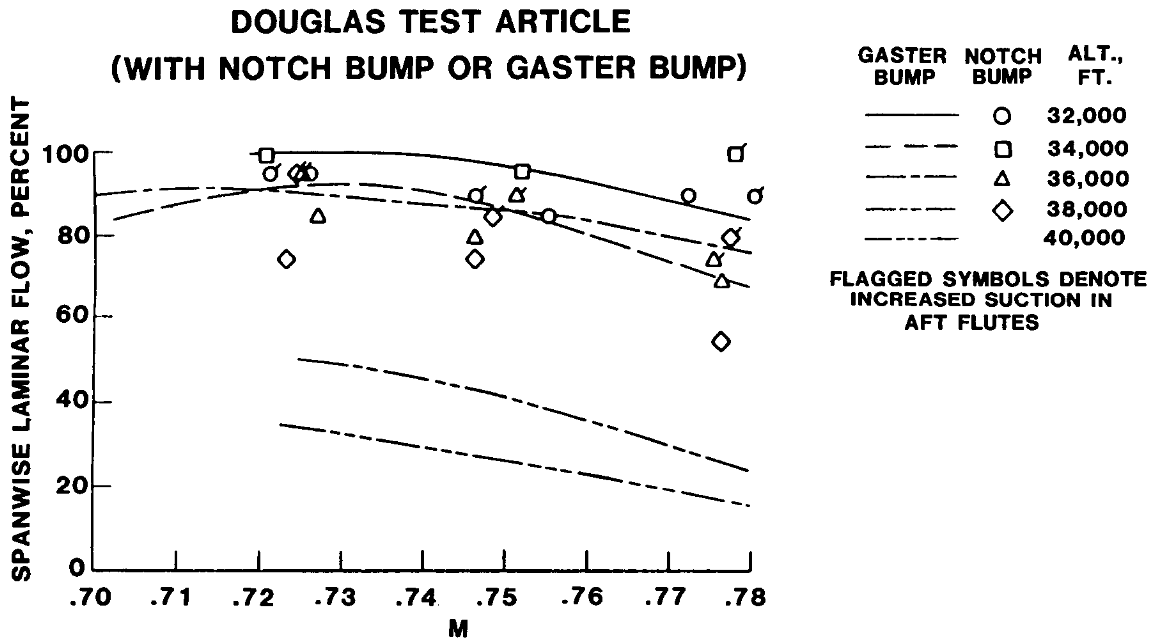
SIDE VIEW



FRONT VIEW

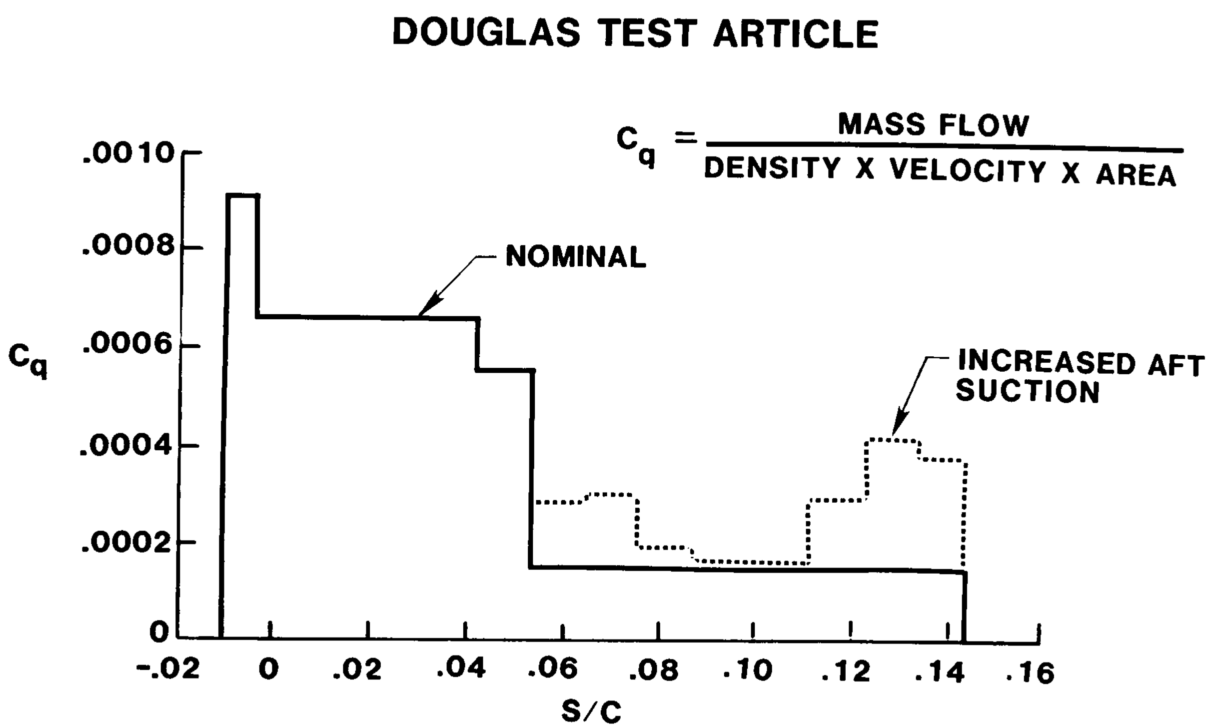
SPANWISE EXTENT OF LAMINAR FLOW AT FRONT SPAR
DOUGLAS TEST ARTICLE (WITH NOTCH/BUMP OR GASTER BUMP)

A comparison of the results obtained with the Gaster bump and the notch/bump shows the latter to be the most effective in controlling the turbulence contamination. With increased suction in the aft flutes (see following figure) nearly the entire span of the test article has laminar flow at the front spar over the operational flight envelope.



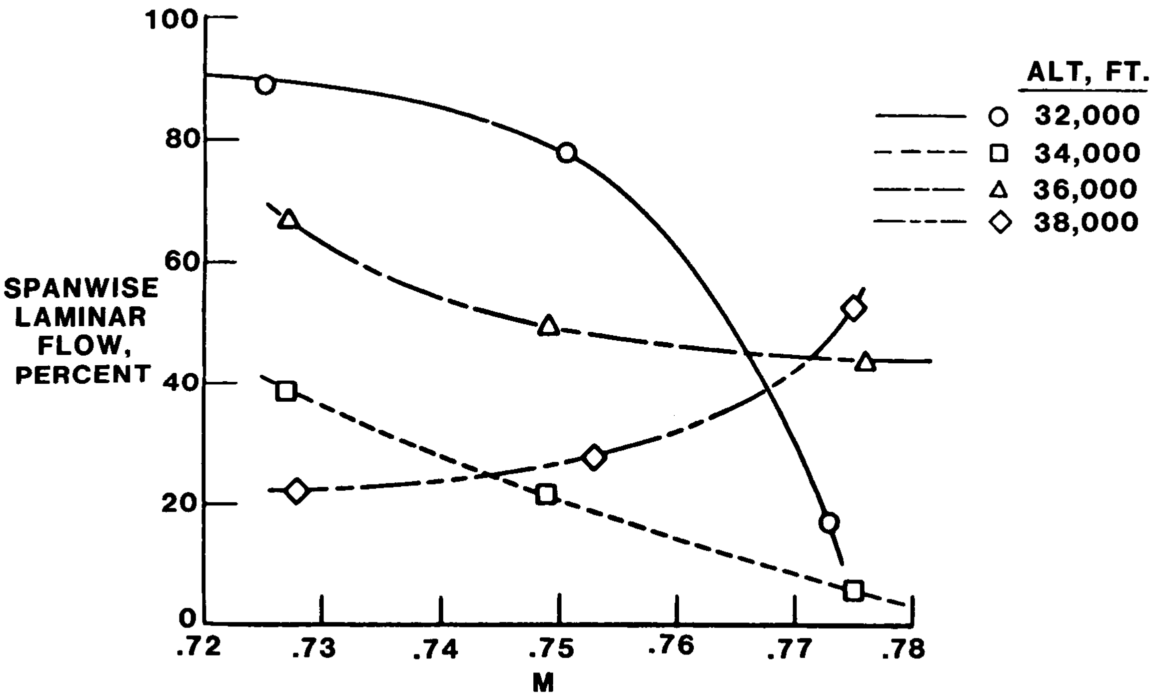
SUCTION DISTRIBUTION

Further improvements in the spanwise extent of laminar flow with the notch/bump were achieved with increased suction in the aft flutes of the Douglas test article. These suction increases were made after data analyses indicated some outflow due to spanwise surface pressure gradients in this area.



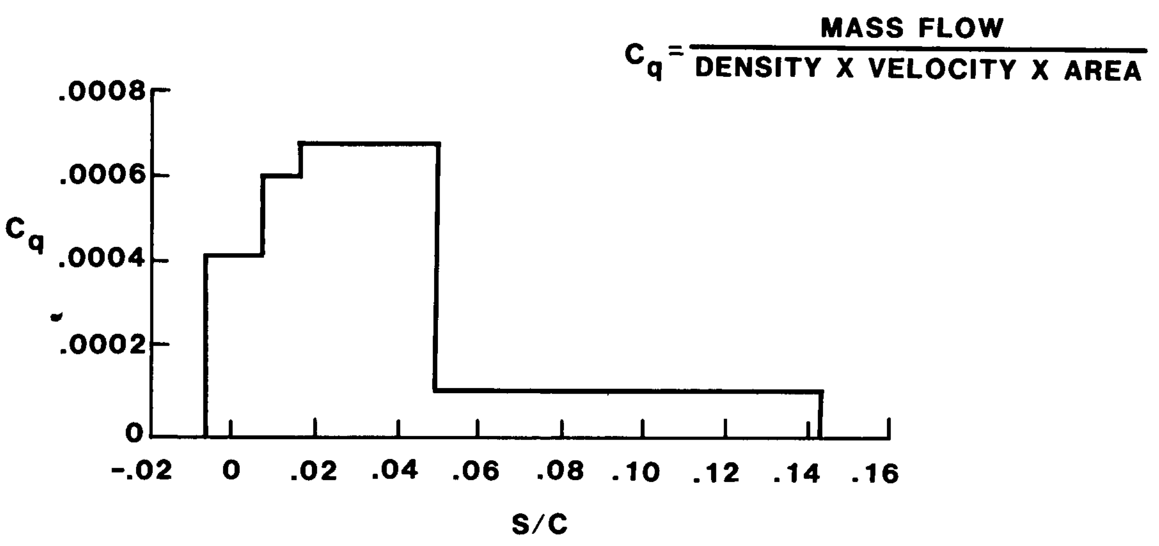
SPANWISE EXTENT OF LAMINAR FLOW AT FRONT SPAR
LOCKHEED TEST ARTICLE (WITH GASTER BUMP) - UPPER SURFACE

The Gaster bump greatly improved the performance of the Lockheed test article; however, the achievement of laminar flow is still quite limited. Our plans are to duplicate the notch/bump configuration used on the Douglas test article and retest the Lockheed article.



NOMINAL SUCTION DISTRIBUTION
LOCKHEED TEST ARTICLE - UPPER SURFACE

The suction distribution on the Lockheed article is similar to the Douglas suction distribution. Unlike the Douglas test article (which has suction along the attachment line), the first slot on the Lockheed article is located downstream of the attachment line at the cruise design point.



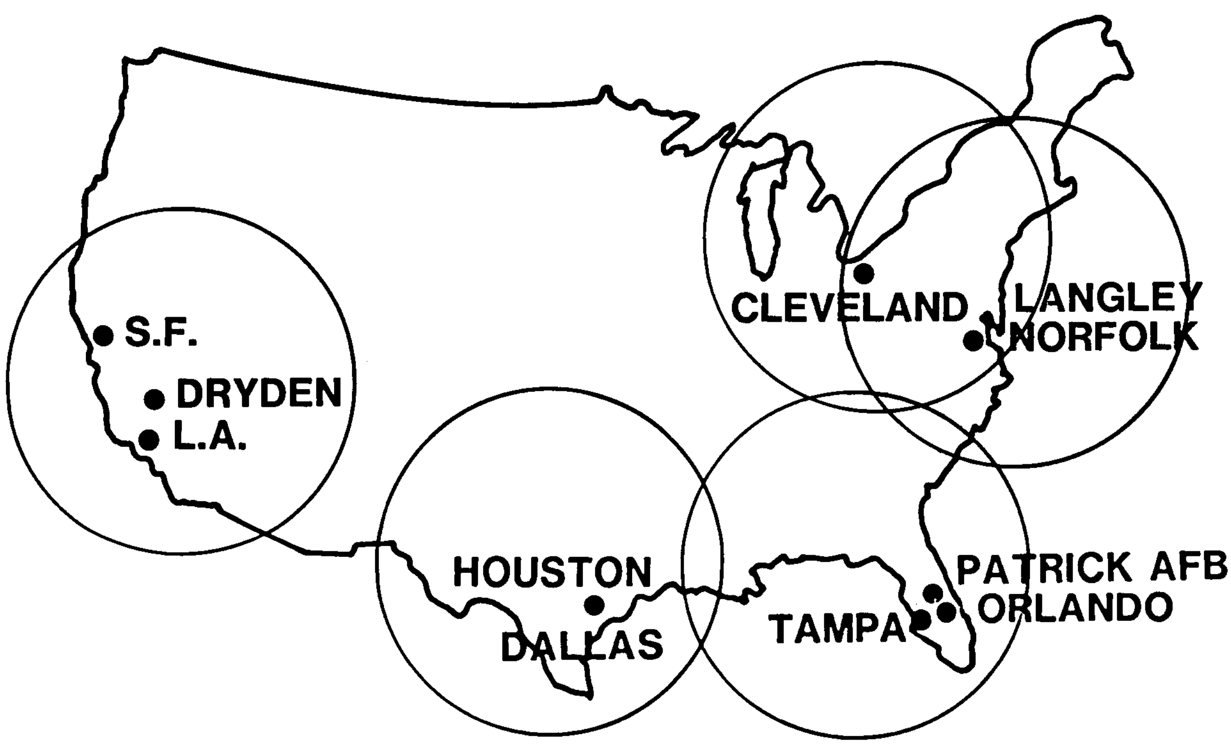
JETSTAR LEFT RESULTS - MARCH 1985

During the past year, good progress has been made in the flight test program. The design pressure distribution goals have been achieved. The in-flight washing and ice protection systems have been operated and function as designed. With the addition of a passive device to suppress leading-edge turbulence contamination, nearly full span laminar flow has been achieved on the Douglas test article over the operational cruise speed and altitude range of the JetStar. A maximum of 85% spanwise extent of laminar flow has been achieved on the Lockheed test article with a Gaster bump at M = 0.725 at 32,000 feet; the prospects for further improvements are believed to be good.

- **Design pressure distribution goals achieved**
- **In-flight washing and ice protection systems function as designed**
- **Douglas test article nearly fully laminar at altitudes up to 38,000 ft. with notch/bump**
- **Lockheed test article laminar for 85 percent of span at M = 0.725, alt = 32,000 ft with Gaster bump**

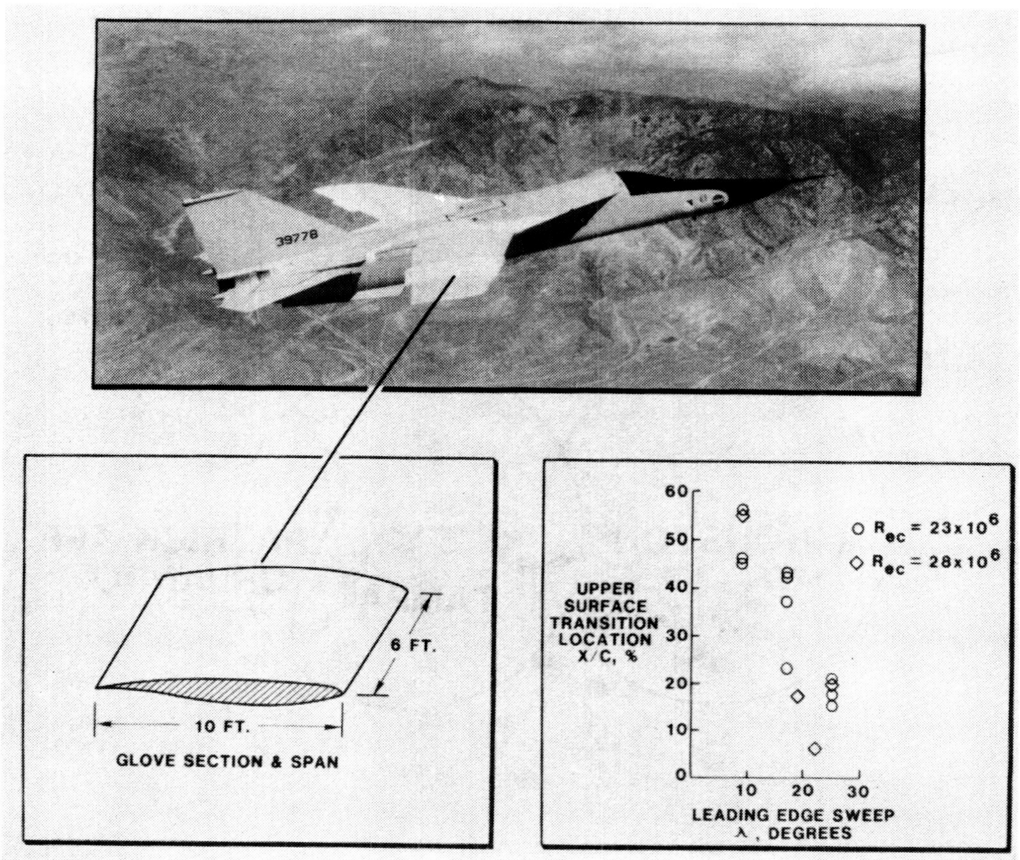
SIMULATED SERVICE HOME BASES

In the summer of 1985, we intend to initiate a simulation of airline service operations. The aircraft will be operated out of home bases throughout the United States. Operation of the laminar flow systems will rely heavily on the experience accrued in the earlier phases of flight testing. The JetStar will operate for approximately a 2-week period from each home base flying into and out of major commercial airports. Two or more flights will be conducted daily, with each consisting of takeoff, climb-to-cruise altitude, achievement of laminar flow for some minimal period, descent, landing, and inspection of the test articles. The condition of the test articles (possible insect remains, clogged or contaminated suction surfaces, etc.) will be fully documented after each flight. Special measures to clean or otherwise maintain the test article surfaces or systems will be minimal in order to establish a maintenance and reliability data base.



TACT NLF GLOVE AND TEST RESULTS

Recent NASA research is encouraging with regard to the prospects of obtaining significant amounts of laminar flow on small commercial transports with natural laminar flow (NLF) or a hybrid of natural laminar flow and laminar flow control (LFC). In 1980, the TACT (F-111) aircraft at the NASA Ames/Dryden Flight Research Facility was flown with a full chord, partial span glove designed to achieve natural laminar flow. The glove employed a supercritical NLF airfoil. In these flight tests (ref. 5), extensive laminar flow was observed at moderate wing sweeps suggesting that NLF could be a design option provided wing sweep is not excessive. The sweep limitation of natural laminar flow might be overcome by a hybrid laminar flow control (HLFC) concept, which shows attractive gains from combining LFC suction in the leading-edge region with NLF over the wing box. The suction in the leading-edge box controls the strong crossflow disturbances that occur initially on swept wings; over the wing box the pressure distribution is tailored to provide favorable gradients to stabilize the two-dimensional disturbances.



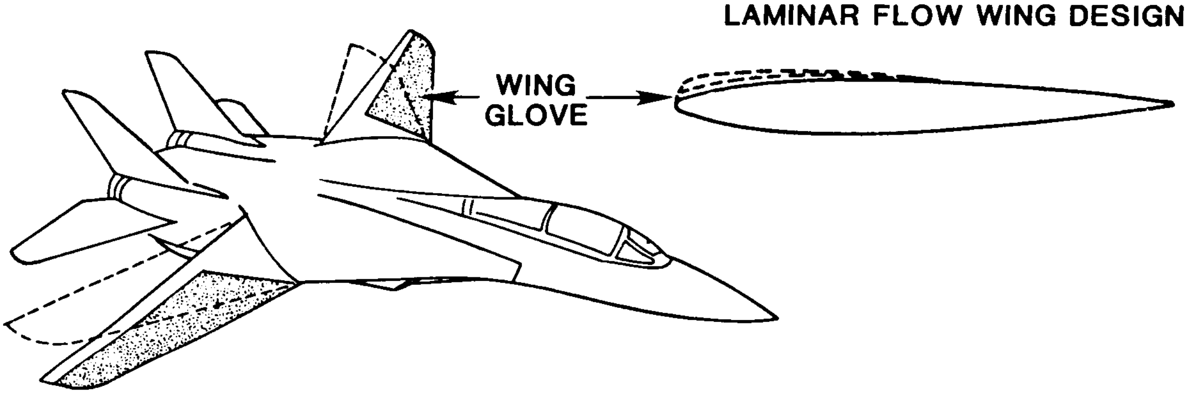
VARIABLE SWEEP TRANSITION FLIGHT EXPERIMENT

At present, transition data applicable to swept wings with NLF or HLFC pressure distributions are limited and are needed in order to make valid assessments of the potential of NLF or HLFC wings for transports of various sizes and speeds. A flight program has been initiated to provide a transition data base for such wing designs. An F-14 aircraft with variable wing sweep capability will be modified with three full-span gloves to produce a range of upper surface wing pressure distributions. The gloves will be constructed of foam and fiberglass with no provisions for suction and scabbed onto the existing wing surface. The gloves will extend from below the attachment line over the upper surface to the spoiler hinge line (about 60% chord). The first glove will be a simple surface cleanup of the basic wing which has a strong favorable pressure gradient over the wing box. The other two gloves have design Mach numbers of 0.7 and 0.8 and were designed by the Langley Research Center and under contract to the Boeing Company respectively. These gloves have more moderate pressure gradients in the wing box area (ref. 6).

OBJECTIVE

ESTABLISH BOUNDARY LAYER TRANSITION DATA BASE FOR LAMINAR FLOW WING DESIGN

F-14



$M_\infty \sim$ 0.7 TO 0.85

SWEEP $\sim 15^\circ$ TO 35°

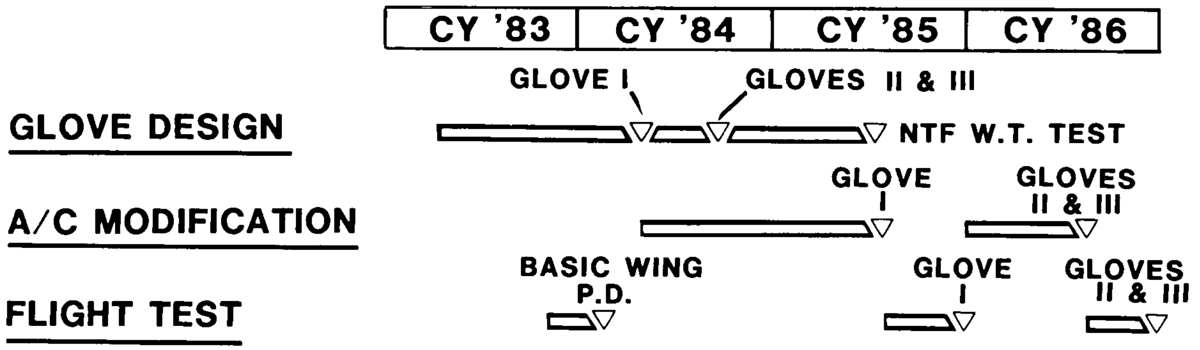
$R_{\infty c_{max}} \sim 30 \times 10^6$

APPROACH

- USE VARIABLE SWEEP AIRCRAFT
- GLOVE UPPER WING SURFACE FROM ROOT TO TIP
- FLIGHT TEST THREE GLOVES
  - WING CLEAN-UP
  - M = 0.7 DESIGN
  - M = 0.8 DESIGN

VARIABLE SWEEP TRANSITION FLIGHT EXPERIMENT

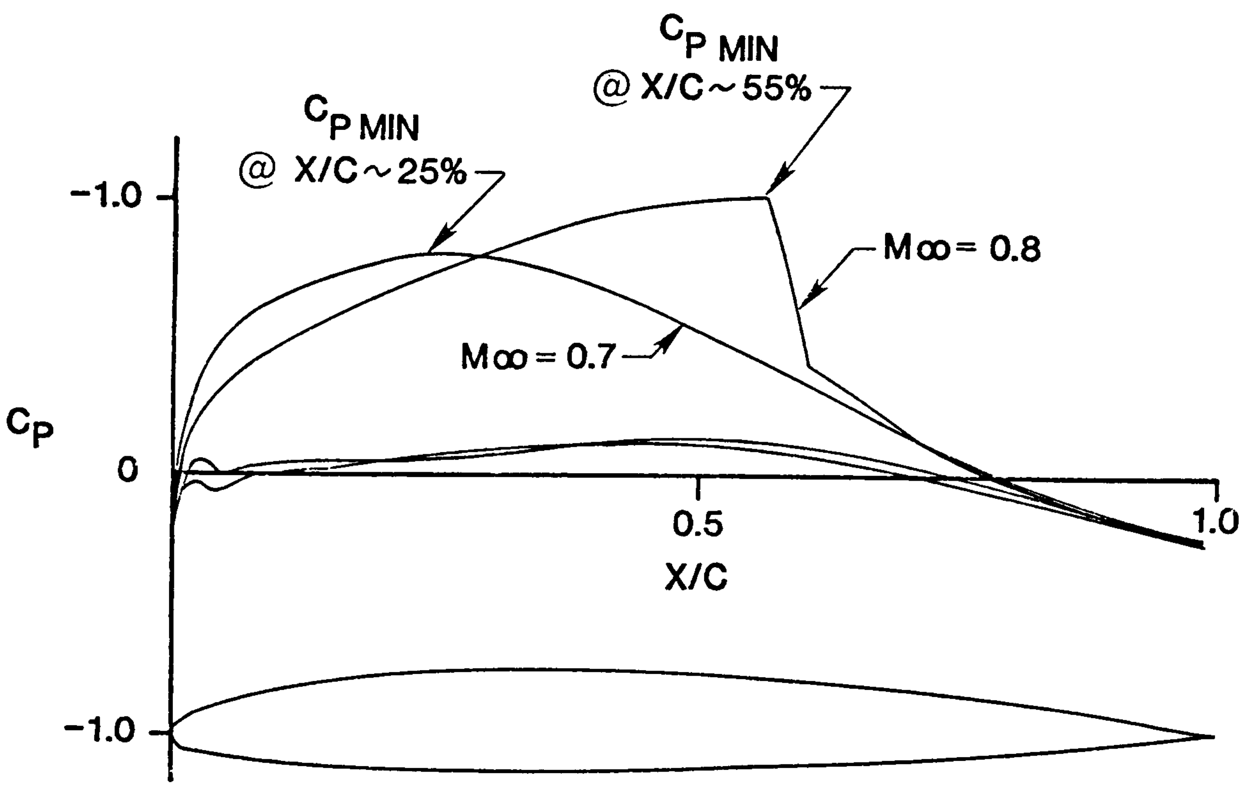
Current plans are to begin flight testing of the clean-up glove in the fall of 1985. Wind tunnel test verification of the other two glove designs will be made in Langley's NTF Tunnel about the same time. Approximately a year later, these gloves will be installed on the aircraft (the M = 0.7 glove on one wing and the M = 0.8 glove on the other wing) and flight tested.



GLOVE I	**WING CLEAN-UP**
GLOVE II	**M = 0.7 DESIGN**
GLOVE III	**M = 0.8 DESIGN**

VARIABLE SWEEP TRANSITION FLIGHT EXPERIMENT
MACH NUMBER EFFECT ON BASIC WING Cp(X/c)

Pressure distributions on the basic F-14 wing are shown for two Mach numbers. The basic wing section is a modified NASA 6 series airfoil. The pressure minimum occurs at 25% and 55% chord for M = 0.7 and 0.8, respectively.

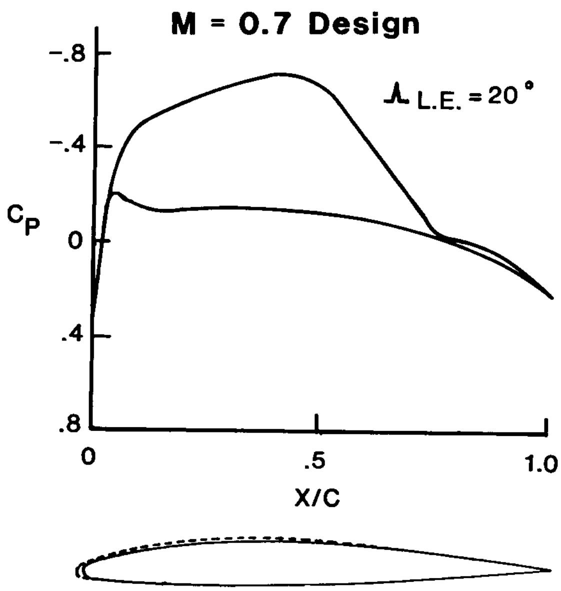


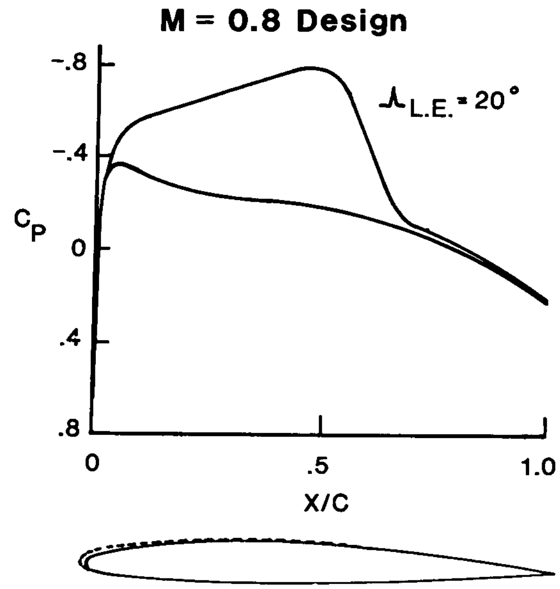
F-14 CLEAN-UP GLOVE FABRICATION

This photograph shows the F-14 wing in a support fixture with the clean-up glove installed. The glove has a constant thickness of 0.65 inch from x/c = 0.05 on the lower surface, around the leading-edge, to x/c = 0.60 on the upper surface. The glove consists of a layer of fiberglass at the wing surface, 0.5 inches of foam, and six layers of fiberglass with a sailplane surface finish produced by body filler and paint.

VARIABLE SWEEP TRANSITION FLIGHT EXPERIMENT
GLOVE AERODYNAMIC ANALYSES

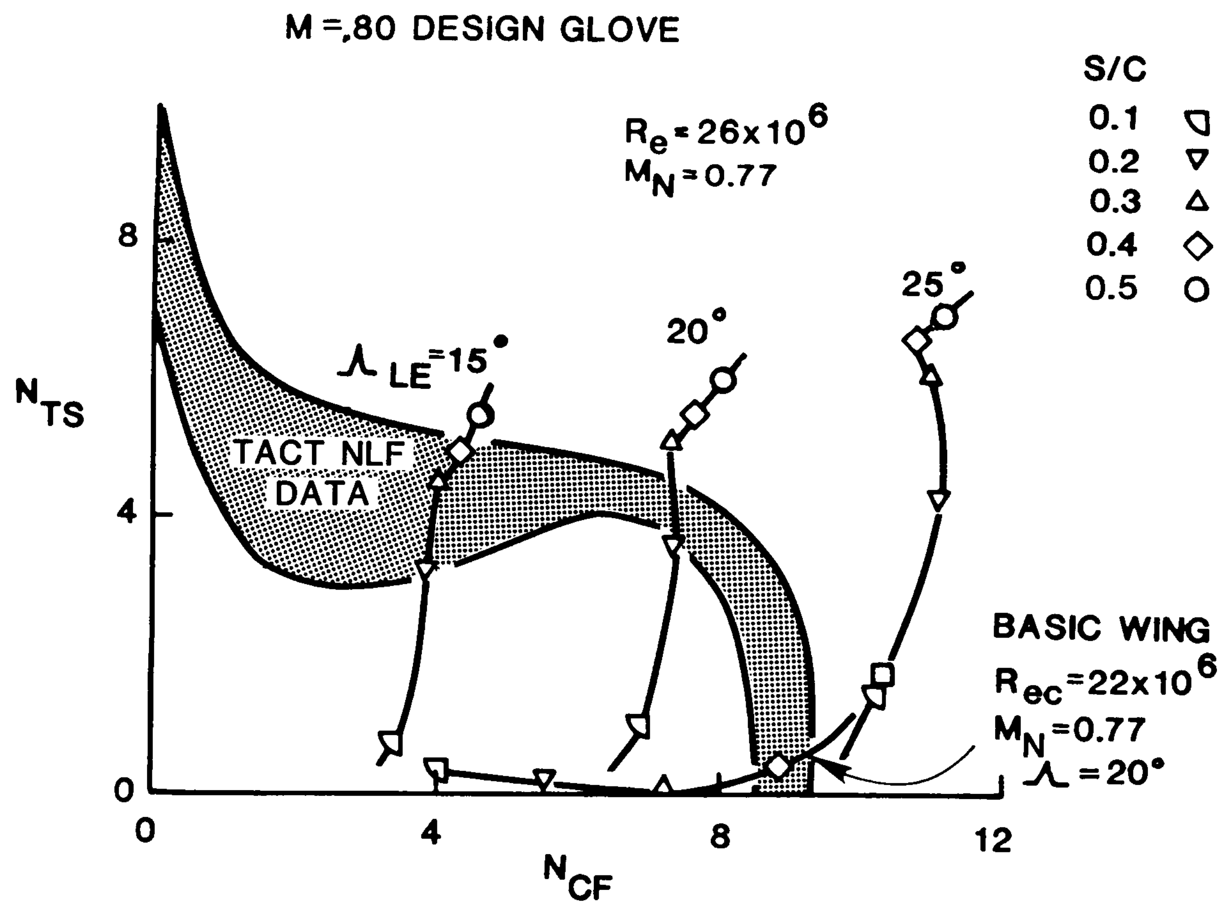
The design pressure distribution at twenty degrees of sweep for the M = 0.7 and 0.8 designs are shown in this figure. Over the wing box the pressure gradient for the two gloves is approximately $dC_p/d(x/c) = -0.75$, somewhat less than the basic wing.





BOUNDARY LAYER STABILITY ANALYSIS

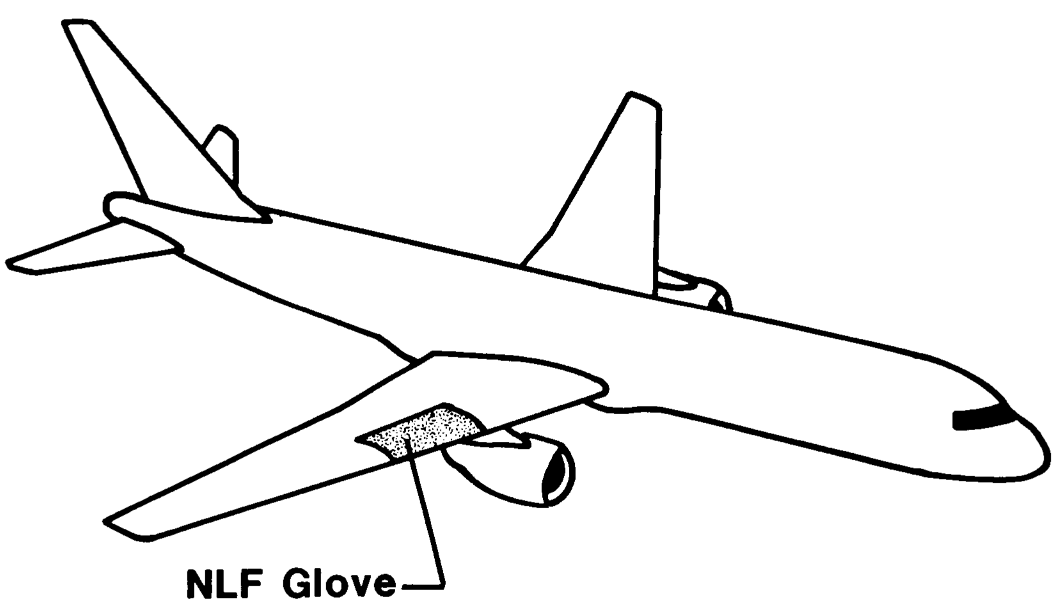
Boeing's analysis of the boundary layer stability for the M = 0.8 glove at Re = 26 x 10 is shown for three wing sweeps. At each sweep the flight Mach number will be chosen to produce the normal Mach number component of M = 0.77. M = 0.77 corresponds to M = 0.8 at 20° leading-edge sweep. Results are shown in terms of the N factor growth of crossflow and Tollmien-Schlichting disturbances. Results of a basic F-14 wing analysis are also shown for one condition. The shaded area is a transition correlation performed by Boeing from the analysis of the limited TACT NLF glove data (ref. 7). The basic wing boundary layer transition should be crossflow dominated over the range of flight conditions. With the variable sweep capability, however, the M = 0.8 design should provide a wide range of interactions between crossflow and Tollmien-Schlichting disturbances.



757 WING NOISE SURVEY AND NLF GLOVE FLIGHT TEST

The acoustic pressure field impinging on the surface of a wing with natural or controlled laminar boundary layers can cause transition to turbulent flow if the fluctuating acoustic pressures are of sufficient amplitude and in an unstable frequency range for the laminar boundary layer. Very little acoustic environment data measured on the wing of an aircraft are available. The available data show that the sound pressure levels on the surface of a wing with wing-mounted engines are significantly higher than those on the wing of an aircraft with engines installed on the aft fuselage. However, this does not necessarily preclude the application of laminar flow techniques to configurations with wing-mounted engines. To avoid possible design limitations, NASA has contracted with the Boeing Company to perform a flight test program using the Boeing 757 research aircraft with wing-mounted high-bypass ratio engines to obtain accurate and comprehensive acoustic environment data on the wing surfaces. As part of this effort, a section of the wing will be modified with a natural laminar flow glove to allow direct measurement of the effect of varying engine power setting on the extent of laminar flow.

The objectives of the 757 wing noise survey and the NLF glove flight test are to: (1) measure the engine-generated acoustic environment on the surfaces of a wing of a 757 with a PW 2037 high-bypass ratio engine, and (2) directly measure the effect of engine noise on the extent of natural laminar flow on a portion of the wing near the engine.



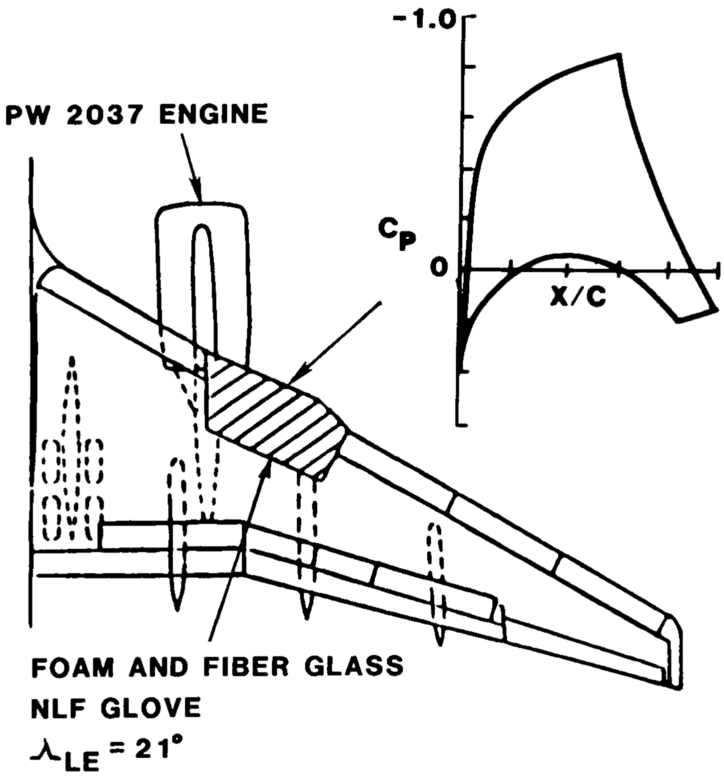
OBJECTIVES:

- **Measure acoustic environment on wing surface**
- **Measure effect of engine noise on extent of NLF**

757 WING NOISE SURVEY AND NLF GLOVE FLIGHT TEST

The NLF glove will be installed on the 757-200 left wing immediately outboard of the number one engine. The slat outboard of this engine will be removed and replaced with a glove which will consist of a dense rigid foam block with a structural supporting beam and ribs, covered with a smooth fiberglass surface. The leading-edge sweep of the glove will be 21 degrees. The glove will be instrumented with surface pressure orifices, hot films for transition detection, and flush microphones. Microphones on the remainder of the wing will be used to survey the wing acoustic environment. Both the upper and lower surface of the wing and glove will be instrumented.

The desired glove pressure distribution near its mid-span location is shown in the figure. An estimated 3-5 feet of chordwise extent of laminar flow will occur in the absence of engine noise. The effect of engine noise on the extent of laminar flow will be determined by varying the engine power setting at given flight conditions.



CONTRACTOR

BOEING COMMERCIAL AIRPLANE COMPANY

FLIGHT CONDITIONS

- $0.6 \leq M_\infty \leq 0.84$
- 30K ft. $\leq$ ALT. $\leq$ 41K ft.
- 3 TO 5 FT. OF LAMINAR FLOW

MEASUREMENTS

NLF GLOVE:

- SURFACE STATIC PRESSURES
- SURFACE HOT FILMS
- FLUSH MICROPHONES

WING SURFACE:

- FLUSH MICROPHONES
- AERODYNAMIC MICROPHONES

757 WING NOISE SURVEY AND NLF GLOVE FLIGHT TEST SCHEDULE

Contract go-ahead was in November 1984. Parts manufacture will be completed in April, at which time the aircraft will be laid up for modifications. The flight test occurred in June 1985 and we expect a final data report to be issued in 1985.

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